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Mass Transfer Between Stars: Photometric Studies

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1. Introduction

This chapter discusses photometric methods of studying mass transfer between stars in close binary star systems, and explains how researchers use the variations in the light received from far away stars to determine the properties of the stars and the nature of mass flow between them. A new photometric method of modelling mass transfer in a certain class of binary stars is introduced.

Binary systems undergoing mass exchange are said to be *interacting* and are referred to as *interacting binary stars*. The interacting binaries discussed in this chapter are Algol-type binary stars (see Section 2), or similar systems. Considerable attention in the field of interacting binary stars has recently been paid to systems containing compact objects (white dwarfs, neutron stars, black holes, etc.) and has left many systems of more normal stars, such as Algols, neglected. This circumstance actually provides opportunities for researchers to study those systems that have been studied in the past century, but have been neglected over the last couple decades. Some emphasis in this chapter is placed on a certain class of interacting binary stars that undergo strange variations in light.

Basic concepts such as the *light curve* and *ephemeris* determination are introduced in section 3. Section 4 explains how a time-dependent ephemeris can be detected and used to calculate the rate at which an interacting binary's orbital period is changing due to mass transfer between the stars, and also to calculate the rate at which the mass is transferring. The *ephemeris curve* is an important tool in the photometric study of interacting binary stars because it is used to verify that mass transfer is taking place.

As the study of interacting binaries continues, we're learning more about their evolution. Interacting binaries can even be used as a sort of laboratory for testing current theories of stellar evolution. Throughout our studies, we've learned that mass transfer between stars can be quite variable. Accretion structures have been detected around the mass-gaining component, and it has been determined that the presence and/or stability of the accretion structures depend on several factors including the size and period of the system's orbit. The mass transfer stream in Algol systems with short orbital periods (about 3 days or less) strikes the accreting star more directly and an accretion disk is not likely to form. On the other hand, stable accretion disks do tend to form in systems with longer orbital periods (greater than about 6 days), where the accretion is not as direct. Systems with intermediate periods can exhibit wild variations, on timescales as short as one orbital cycle or less, due to a variable or transient accretion structure resulting from the system's oscillations between states of direct

impact and indirect accretion. It is in these intermediate-period systems that we can find variations due to eccentric and transient accretion structures (Reed et al., 2010). The sources of other variations in these interacting binary systems include magnetic activity cycles in a component of the system or the existence of a third, more distant, star in the system.

The light curve and ephemeris curve are considered in more detail in Sections 5 and 6. Section 5 discusses the possible causes for periodically variable ephemeris curves, which include magnetic activity and the light-time effect of multiple stars in the system. Section 6 explores the outside-of-eclipse variations that can be used to map out the eccentric accretion structures in intermediate-period interacting binary systems.

2. Algols

Algol-type binary star systems are named after the first one discovered, β Persei, or "Algol". The discovery and analysis of β Per and other similar stars posed an apparent problem than became known as the "Algol Paradox", which has relatively recently been understood through the consideration of mass transfer between stars in binary star systems. The paradox arose from the fact that astronomers were finding binary stars consisting of a less massive, but more evolved, star paired with a more massive and less evolved companion. The problem with this combination was that, according to the widely accepted models of stellar evolution, more massive stars are known to evolve more quickly than less massive ones. Since both stars in a given system are born at the same time, the existence of the Algol-type binaries seemed at odds. The answer, of course, is that mass can transfer between stars in close binaries. The more evolved (giant or sub-giant) star donates mass to the less evolved (main-sequence) star, beyond the point of reversing their mass ratio, leading to Algol-type systems.

3. The light curve

The primary tool used in the photometric study of variable stars is the light curve, which is simply a plot of the brightness of the star versus time. We will focus on light curves of interacting binaries which are eclipsing from Earth's perspective.

On a light curve, the brightness could be given in absolute flux units such as $\text{erg s}^{-1}\text{cm}^{-2}\text{\AA}^{-1}$, relative flux that is normalized to a specific orbital phase value, or stellar magnitude. Time could be in days (Heliocentric Julian Date, or HJD) or in orbital phase values. Julian Date is a continuous counting of whole days, starting with 1 January 4713 BC, and can be calculated from the calendar date of the observation using a standard algorithm. Many groups, such as the United States Naval Observatory, offer on-line conversions between calendar date/time and Julian Date (<http://aa.usno.navy.mil/data/docs/JulianDate.php>).

The method of CCD photometry compares the brightness of the target with comparison stars in the same field of view. Since we use the known magnitudes of the standard, non-varying comparison stars, the primary result of the data reduction is the magnitude of the target at the time of the observation. In order to analyze the light curve using specialized modeling programs such as the Wilson-Devinney code, stellar magnitudes should be converted to relative flux, and HJD should be converted to orbital phase.

To convert stellar magnitude to relative flux, the following formula is used:

$$\text{Relative Flux} = \frac{L}{L_{\text{norm}}} = 10^{((M_{\text{norm}} - M)/2.5)} \quad (1)$$

where M is the measured stellar magnitude of the system at the orbital phase being plotted, and M_{norm} is the stellar magnitude of the system at the orbital phase that is being used as the normalization phase. The normalization phase is generally chosen to be when the system is not eclipsing and its brightness is near maximum. L and L_{norm} refer to the luminosity of the system at the phases described above. Thus, the relative flux is set to 1.0 at the normalization phase, and is equal to a relative value throughout the rest of the system's orbit.

A binary star system's ephemeris is used to convert the HJD of the observation into an orbital phase value. Before defining the ephemeris, let's consider the observational light curve in Figure 1. Here we have stellar magnitude plotted against HJD.

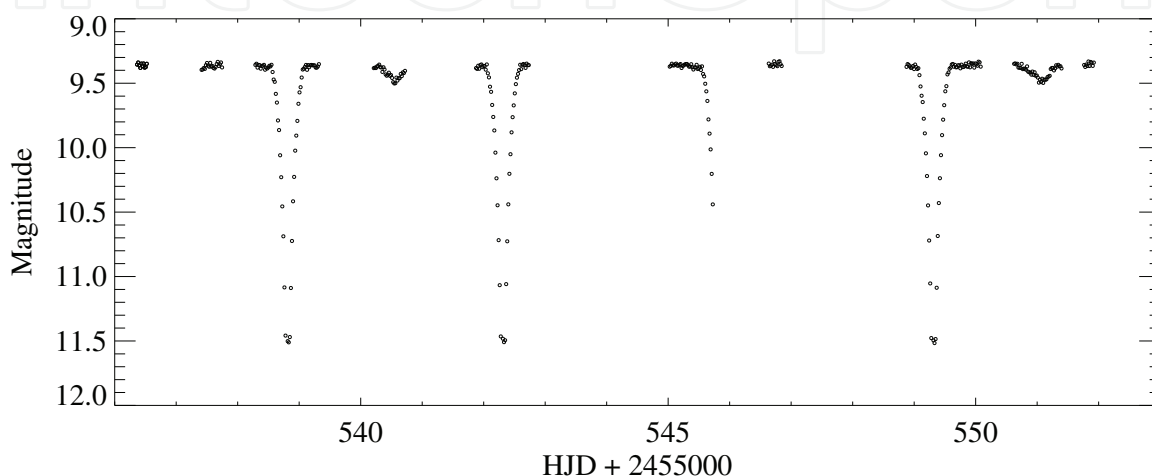


Fig. 1. An example observational light curve of a theoretical binary star system.

This light curve contains data taken over several days time and spans a few complete orbital cycles. The deepest dips in the light curve are due to the *secondary star* (cooler/dimmer) passing in front of the *primary star* (hotter/brighter), and is called the *primary eclipse*. The *secondary eclipse* is not as deep and is caused by the primary star passing in front of the secondary star. We define the center of the primary eclipse as *phase zero* ($\phi = 0$). The rest of the orbital phase values range between 0 and 1, with $\phi = 1$ being the center of the primary eclipse again. For circular orbits, the secondary eclipse occurs at $\phi = 0.5$.

If we analyze the light curve of Figure 1, we would see that the orbital period is 3.50 days, with entire primary eclipses observed at HJD2455538.8125, HJD2455542.3125, and HJD2455549.3125. The *ephemeris* is a formula for calculating future *times of minimum light* (or times of primary eclipses). The ephemeris contains one known time of primary minimum and the orbital period. The ephemeris for this example would look like this:

$$HJD_{Pr.Min.} = 2455538.8125 + 3.5000E \quad (2)$$

where E is an integer equal to the number of complete orbital cycles of the system between the known primary minimum (HJD2455538.8125) and the calculated eclipse time.

So, to convert an observation's HJD to orbital phase, the following procedure is followed. Subtract the known time of primary minimum from the observation's HJD, then divide the difference by the orbital period and truncate the whole number (the decimal part is equal to the orbital phase). For instance, the observation taken at HJD2455546.6702 would be given an orbital phase value like this:

$$\frac{(2455546.6702 - 2455538.8125)}{3.5000} = 2.245 \rightarrow \phi = 0.245 \quad (3)$$

In this example, we will use $\phi = 0.25$ as the normalization phase for converting stellar magnitudes to relative flux values. Figure 2 shows the normalized light curve for the system. Notice that all of the data in Figure 1 are plotted in Figure 2. In practice, it might take several months to years of observations to build a good light curve. A normalized light curve folds all of the available data into one orbital phase and enables all of the data to be used to model the stars in the system.

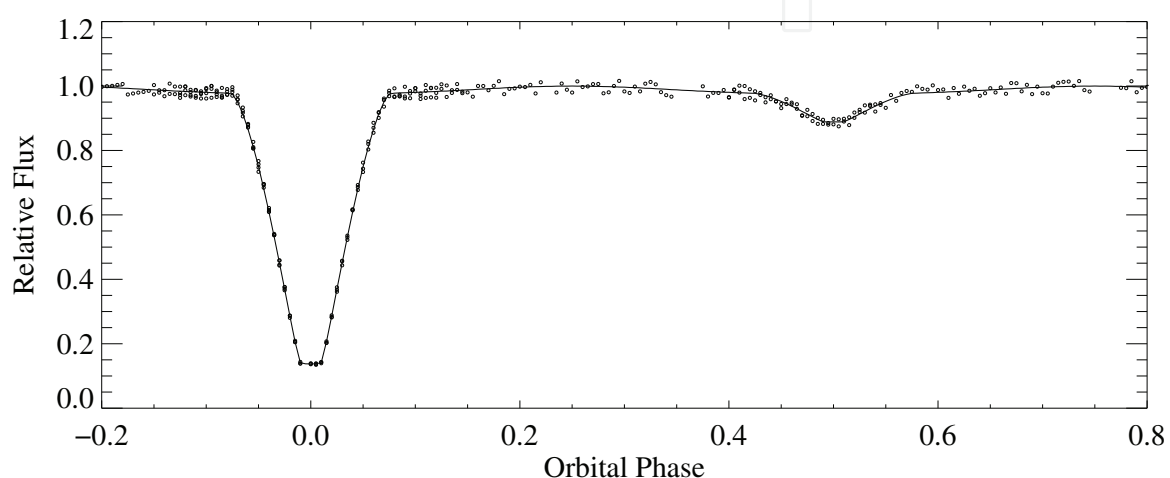


Fig. 2. The normalized light curve of the theoretical binary star system. The solid line is the synthetic light curve produced by the model.

The most widely used method of modelling an eclipsing binary star system is the Wilson-Devinney (W.D.) code (Wilson & Devinney, 1971). The W.D. code's input parameters include the masses, sizes, and surface temperatures of the stars in the system. Other parameters such as *reflection* (the heating of the near side of the cooler star by the hotter star), *limb darkening* (the surfaces of a star that are closer to the center are hotter and brighter than the surfaces that are farther from the star's center), and *orbital inclination* (the orientation of the system's orbital plane relative to our line of sight; an inclination of 90° is edge-on and 0° is face-on) are also standard parameters in the W.D. code.

The theoretical system discussed in this section consists of a primary star with a surface temperature of 12,000 K and a secondary star with a 6,000-K surface temperature. The mass ratio is $q = 0.25$, which means the primary has 4 times the mass of the secondary, and the orbital inclination of the system is 90° . The solid line in Figure 2 shows the synthetic light curve obtained from modelling these parameters with the W.D. code.

Figure 3 illustrates three-dimensional models of the stars at various orbital phase positions. It can be seen that the secondary star has evolved and expanded into a red giant or sub-giant. The secondary star's shape is distorted into a "tear-drop" shape due to the gravity of the nearby primary star. The secondary would be donating mass to the primary star in this case, as is the case with most Algol-type systems.

The W.D. code also allows for *spots* to be incorporated into the modelled light curve. Spots are circular areas on a star's surface and are given a size (radius), location (stellar latitude and

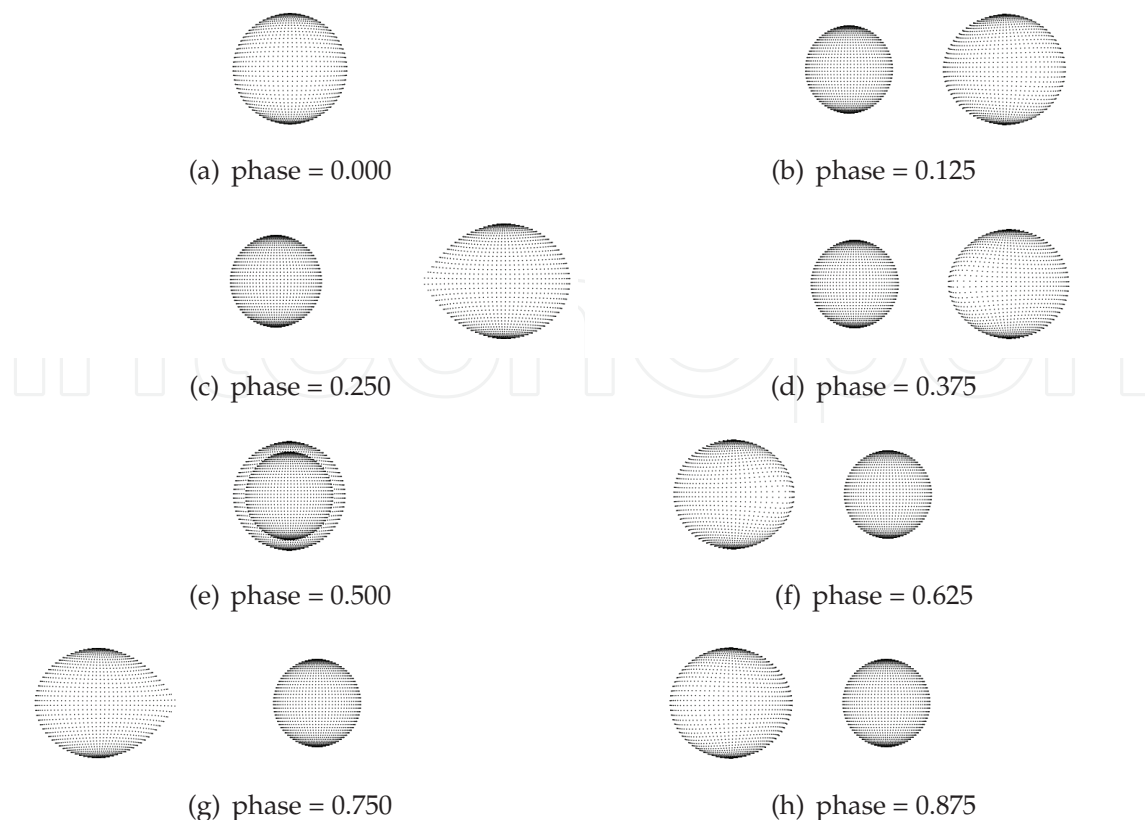


Fig. 3. These are 3-D models of the star system at various orbital phase positions. These models correspond to the synthetic light curve (solid line) plotted in Figure 2, created using the W.D. code.

longitude), and temperature (which could be cooler or hotter than the star's surface). Cool spots are generally used to model regions where magnetic field activity has cooled parts of a star's surface, very similar to Sunspots on our Sun. Hot spots have been used to explain "humps" in a binary star's light curve, and are evidence of mass transfer between stars. Hot spots arise from the region where the mass flow stream from the mass losing star impacts the accreting star. This type of modelling has been referred to as *eclipse mapping*.

A new technique, presented in Section 6, actually incorporates large cool spots in the model to estimate the effect of an eccentric accretion structure eclipsing the primary star. This effect may explain the existence of unexpected dips, and other variations, in the light curve outside of primary and secondary eclipses.

4. The ephemeris curve

The most direct photometric evidence for mass transfer between stars in a binary star system is the observed time-dependent change in the orbital period, or ephemeris, of the system. However, the detection of such a change usually takes some time. A changing ephemeris is typically not detectable with any less than a decade or two of data.

The basic idea is that as material is exchanged between stars in an interacting binary system, the center of mass of the system shifts toward the star that is gaining mass. As a result, due to the conservation of angular momentum, the orbital period of the system will also change. If the more massive star is gaining mass (as is the case with most Algol-type systems), we would

expect the orbital period of the system to continually increase. If the mass accreting star is less massive than the mass donor, then we would expect the orbital period to decrease over time. A binary star's ephemeris is used to calculate future times of eclipses, or minima. Let C be the *calculated* time of a future eclipse. When the night of the calculated eclipse time arrives, and we observe the actual time of the eclipse, we can compare the exact *observed* (O) time with the calculated time to see if a possible period change has occurred. An *ephemeris curve* is the value $(O - C)$ plotted against the integer E , from the ephemeris. E is simply the number of orbital cycles that occurred between the two eclipse times.

Consider again the theoretical eclipsing binary system from Section 3, whose 3.5000 - day orbital period is given in its ephemeris (Equation 2). Figure 4 shows some possible ephemeris curves for that system, which span 9,000 orbital cycles, or about 85 years. Figure 4(a) indicates no observed orbital period change, since O is equal to C and $O - C = 0$ throughout the 85 years of observations. Figure 4(b) also indicates no observed orbital period change, as the best-fit to the ephemeris curve is linear. A linear ephemeris curve, such as this, simply means the orbital period used in the ephemeris is incorrect. One could find an orbital period that, when applied to the ephemeris, would produce a horizontal ephemeris curve (as in Figure 4(a)).

Figures 4(c) and 4(d) both reveal observed period changes. Both are best fit with quadratic functions. The quadratic function would be given by:

$$(O - C) = C_0 + C_1 E + C_2 E^2 \quad (4)$$

where C_0 , C_1 , and C_2 are the coefficients in each term of the best-fit function. The coefficient C_2 is used to calculate the rate at which the orbital period has been changing. The period change rate, averaged of the 85 years of observations, is:

$$\frac{dP}{dt} = \dot{P} = \frac{2C_2}{P} \quad (5)$$

where P is the orbital period of the ephemeris used to determine the calculated eclipse times. Figure 4(c) indicates an orbital period that is steadily increasing. The coefficient C_2 is positive for that case. The case in Figure 4(d) is that of a negative C_2 and therefore a steadily decreasing orbital period.

A good, real example of a neglected interacting binary star system is R Arae, which was discovered in 1894 but whose first ephemeris curve was published in February 2011 and is shown in Figure 5. The plot contains all known times of primary eclipse spanning the 116 years from R Ara's discovery through the latest observation of 30 May 2010. The ephemeris used for the plot is the one calculated from observations taken in 1986 (Nield, 1991):

$$HJD_{Pr.Min.} = 2446585.1597 + 4.425132E \quad (6)$$

so, it can be seen that in 1986, the orbital period of R Ara was 4.425132 days. The quadratic function that best fits the data is:

$$(O - C) = (0.0538) + (6.371 \times 10^{-5})E + (1.41 \times 10^{-8})E^2 \quad (7)$$

which means the average rate of period change on the 116 years of observations is:

$$\frac{dP}{dt} = \dot{P} = \frac{2C_2}{P} = \frac{2(1.41 \times 10^{-8})}{4.425132} = 5.16 \times 10^{-9} \frac{\text{days}}{\text{day}} \quad (8)$$

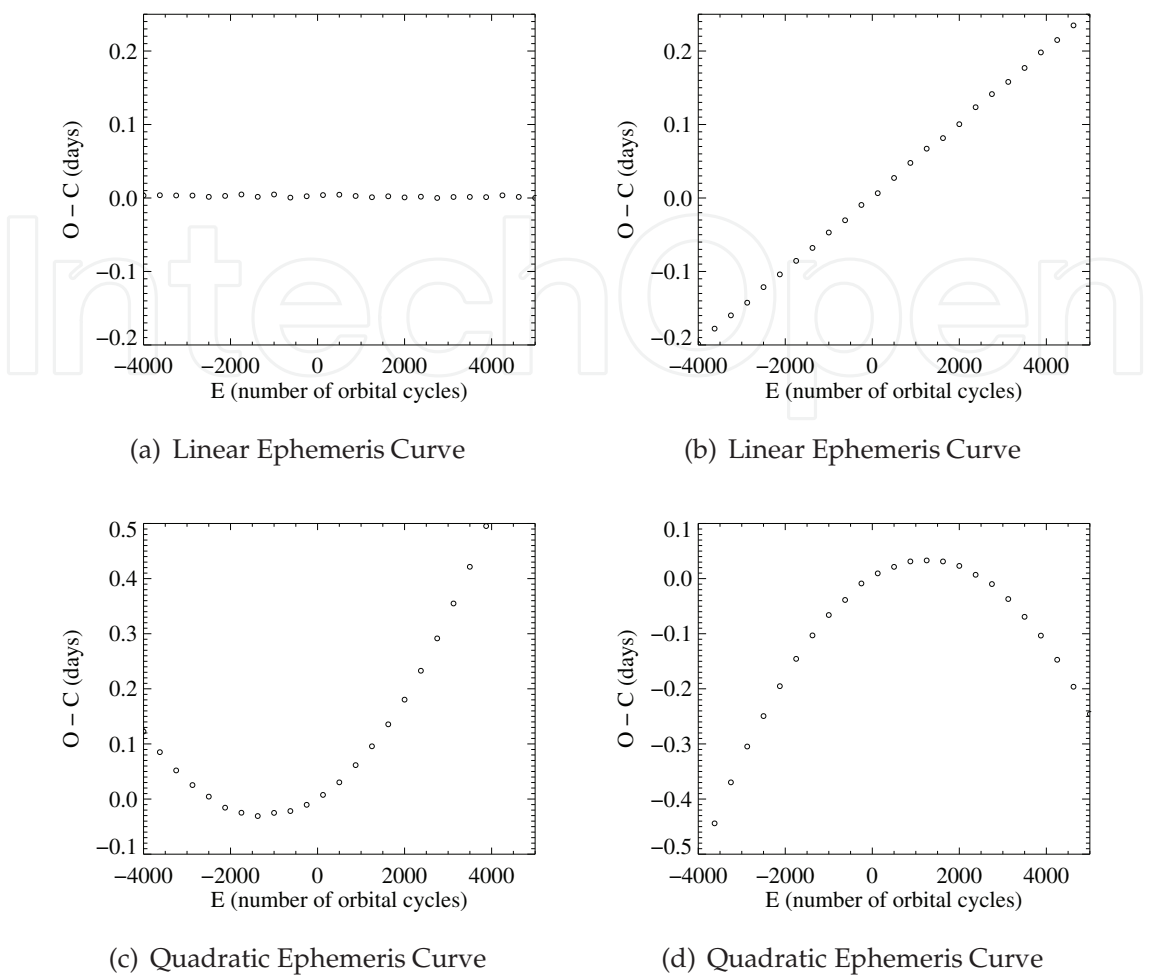


Fig. 4. Linear Ephemeris Curves ((a) and (b)) and Quadratic Ephemeris Curves ((c) and (d)).

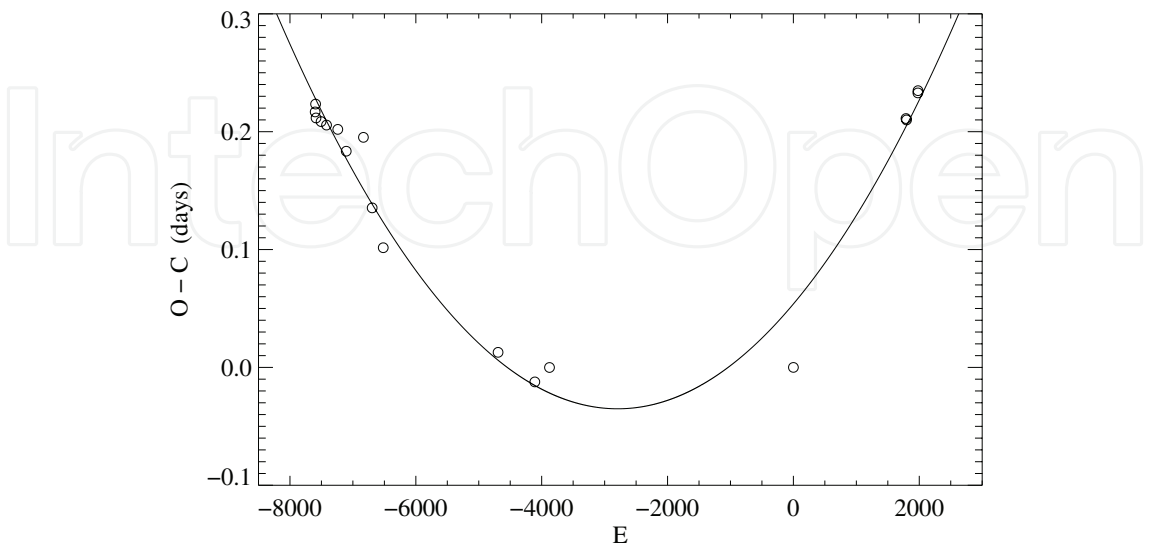


Fig. 5. This is the first ephemeris curve for R Ara. (Reed, 2011)

The average rate of mass transfer from the donating star to the accreting star can be calculated from the period change rate. The calculation requires estimates for the stars' masses and the assumption that the mass transfer is *conservative*. Conservative mass transfer assumes that all material leaving one star is accreted onto the other star, and no mass is lost to interstellar space. Mass transfer is very likely conservative in most Algol-type binaries, but it could deviate from this in the cases of the most active and rapidly interacting systems. The conservative mass transfer assumption, combined with the modified Kepler's laws of orbital motion, leads to the following formula for mass transfer rate:

$$\frac{dM}{dt} = \dot{M} = \frac{\dot{P}M_1M_2}{3P(M_1 - M_2)} \quad (9)$$

where M_1 and M_2 are the masses of each of the two stars in the binary system.

For the case of R Ara, a spectroscopic study (Sahade, 1952) of the system determined the masses of the stars to be $M_1 = 4M_\odot$ and $M_2 = 1.4M_\odot$. (The symbol " \odot " means "Sun", so $1M_\odot$ is equal to the mass of our Sun.)

Applying these masses, and the period change rate (from equation 8), to equation 9, yields:

$$\frac{dM}{dt} = \dot{M} = \frac{\dot{P}M_1M_2}{3P(M_1 - M_2)} = \frac{(5.16 \times 10^{-9})(4)(1.4)}{3(4.425132)(4 - 1.4)} = 8.37 \times 10^{-10} \frac{M_\odot}{day} \quad (10)$$

Finally, converting days to years for the standard units of "Solar-masses-per-year", we get:

$$\frac{dM}{dt} = \dot{M} = 3.06 \times 10^{-7} \frac{M_\odot}{year} \quad (11)$$

which is actually quite rapid for an Algol-type system. For those unfamiliar with these units, the equivalent mass transfer rate of about 20 trillion tons per second might sound more impressive!

A quadratic ephemeris curve is considered strong photometric support for mass transfer between stars. It certainly proves that the orbital period is changing, and it is widely accepted that mass exchange is the most likely cause.

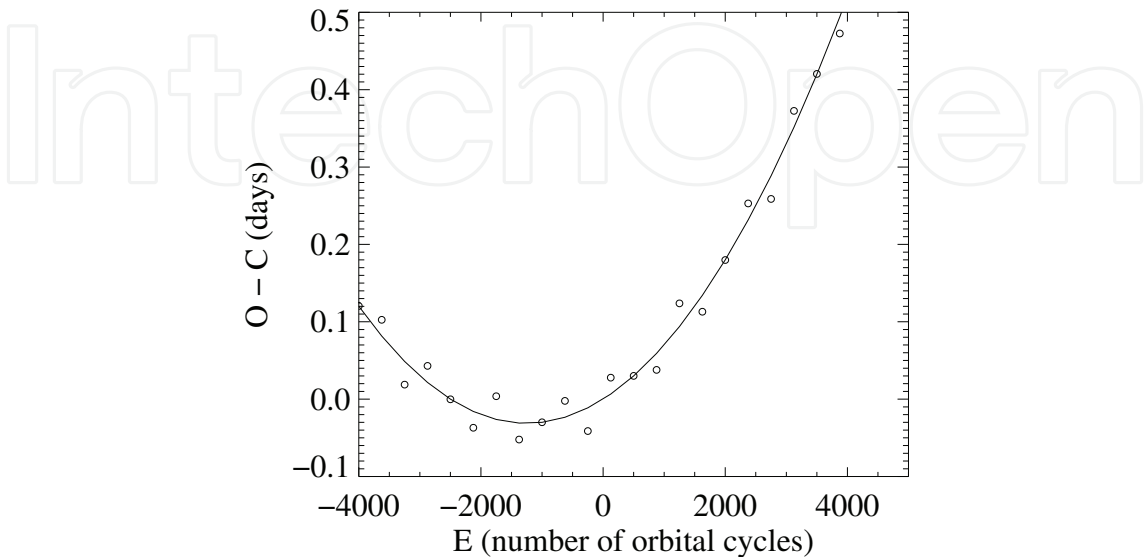
5. Variable ephemeris curves

The previous section described how the analysis of an ephemeris curve is used to calculate rates of period change and mass transfer in interacting binary stars. This section further discusses ephemeris curves and the additional information they may provide.

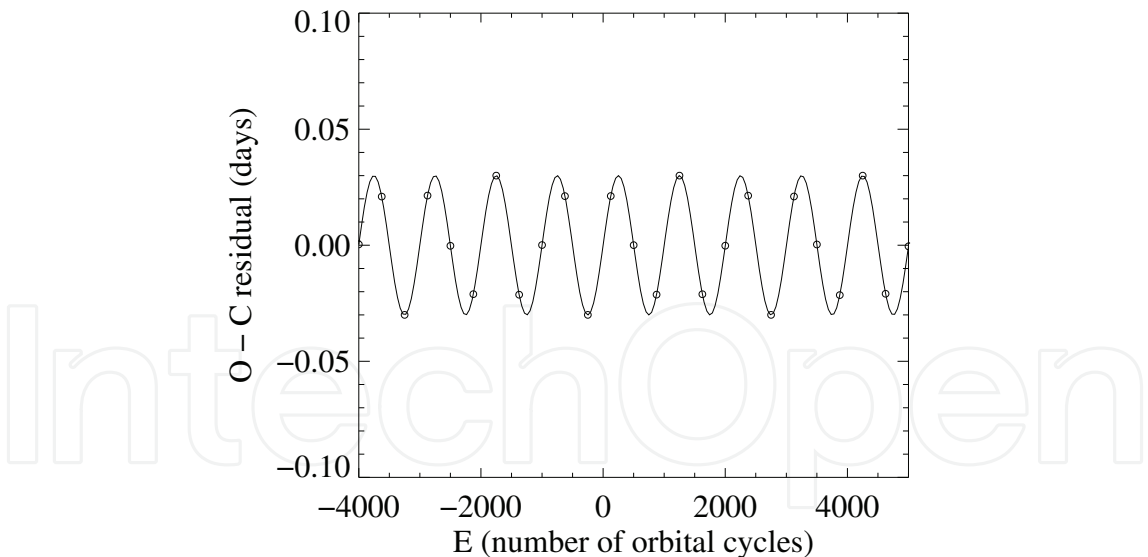
Consider the plot in Figure 6(a). The ephemeris curve is fit with a quadratic function, which indicates a steady increase in orbital period, and provides evidence for mass exchange. Notice the scatter in the data follows a periodic pattern. Taking the difference between the data points and the quadratic function yields a plot of the residuals of the fit. The residual plot is shown in Figure 6(b). A sinusoidal function fits the residual plot nicely, which seems to indicate a periodical increase and decrease in the mass transfer rate. A sinusoidally varying ephemeris curve could mean one of two things; either there is a third star in the system, or there is significant magnetic activity.

In the case of a third star in the system, the mass transfer rate is not actually varying, but it is just an apparent *light-time* effect resulting from the fact that light travels at a finite speed. If the close, interacting binary system is orbiting around a third, more distant star, then we will sometimes be observing the interacting system when it is on the near side of the larger orbit. Some observations will take place while the interacting system is on the far side of the

triple star system. This circumstance will lead to alternating changes in the observed times of eclipses. The eclipses observed while the interacting system is on the near side will be detected sooner than those occurring while it is on the far side. If the effect is due to a third star in the system, the periodic variation **must** be precise and repeating.



(a) An phemeris curve fitted with a positive quadratic function.



(b) The residuals of the ephemeris curve from Figure (a), fitted with a sinusoidal function.

Fig. 6. This is a periodically variable ephemeris curve.

Periodic variations could also indicate magnetic activity cycles in the evolved star that is donating mass. In this case, the precise repitition of the cycle is not necessary. Our Sun is known to undergo an eleven-year magnetic activity cycle, where the Sun goes through periods

of high activity (Sunspots, Solar flares, prominences, and coronal mass ejections) followed by periods of little to no activity. It is expected that a mass-losing star with strong magnetic activity cycles will donate mass more rapidly during high activity and less rapidly during low activity, which in turn will cause the rate of period change, and therefore the ephemeris curve, to alternate periodically. The period of the sinusoidal residual plot would be equal to the star's magnetic activity cycle period. In the example of Figure 6, the period is 1,000 orbital cycles. If this is for the theoretical star system introduced in Section 3 (orbital period of 3.5 days), the magnetic activity cycle of the star would be approximately 10 years.

Algol-type interacting systems with negative ephemeris curves (as in Figure 4(d)) present another interesting problem. A negative ephemeris curve indicates a decreasing orbital period, but since Algol-type systems consist of a less massive star donating mass to a more massive star, we would expect the orbital period to increase and the ephemeris curve to be positive (as in Figure 4(c)). This contradiction seems to violate the law of conservation of angular momentum.

Possible solutions to this angular momentum problem include *magnetic braking* and non-conservative mass transfer. Magnetic braking is basically the concept that the stars are "dragging" through strong magnetic fields which causes the orbit to decline and the orbital period to decrease. Non-conservative mass transfer implies that some of the mass escaping one star does **not** accrete onto the companion, but rather it either escapes the entire system or forms a *circumbinary* envelope around both stars. The lost mass in the non-conservative mass transfer case would deplete angular momentum from the rest of the system, leading to a negative ephemeris curve.

6. Effects of eccentric accretion structures

The light curves of many Algol-type binary stars show strange variations outside of the primary and secondary eclipses. It has been assumed that these variations arise from mass transfer activity between the stars, but the W.D. code is limited in how it can model such variations. A newly developing photometric method will enable astronomers to use outside of eclipse variations to visualize an eccentric accretion structure surrounding the mass-gaining star.

Experts in the field have determined, using computer modelling and spectroscopic observations, that an Algol system's orbital period (and orbital size) plays an important role in the nature of the mass transfer within the system. As introduced in Section 1, "short-period" Algols (orbital periods ≈ 3 days or less) have smaller orbits and experience direct impact of mass transferring from one star to the other, while "long-period" Algols (≈ 6 days or longer) have wider orbits and develop stable accretion disks. Intermediate-period Algols are found to oscillate between "stream-like" (similar to short-period systems) and "disk-like" (similar to long-period systems) states (Richards et al., 2010). Many intermediate-period Algols exhibit outside of eclipse variations in their light curves, which are likely caused by the unstable, transient, and eccentric accretion structure that develops.

The accretion structure can at times block the view of the primary star, similar to an eclipse, causing dips in the light curve. These dips can vary in intensity, or even disappear, on timescales as short as a single orbital period. Since entire light curves of Algol systems must be obtained over many week or months, it is very difficult to accurately determine the causes of the variations because it is impossible to continuously observe the system through a complete orbit. Observations from the ground can only be made at night, and that's only when skies are clear and free of clouds.

A good example of such an intermediate-period system is R Ara, whose orbital period is 4.4 days. Ground-based light curves of R Ara exhibit strange dips and other variations. Again, these light curves were built over many weeks of observations. But by using the International Ultraviolet Observer (IUE) satellite, a group of astronomers were able to observe R Ara for 5 consecutive days, which provides an uninterrupted light curve. From space, weather and daylight do not impede observations.

Figure 7 shows the ultraviolet (UV) light curve. The solid circles in the figure are the flux levels at 1320 Å and the open circles are at 2915 Å. Notice that the primary eclipse is deeper at 1320 Å and shallower at 2915 Å, which is as expected. Since the primary eclipse is when the hotter star is eclipsed by the cooler star, it is always deeper at shorter wavelengths. Similarly, a secondary eclipse (eclipse of the cooler star by the hotter star) is always deeper at *longer* wavelengths. In the UV range (shorter wavelength than visual), R Ara's secondary eclipse is expected to be very shallow.

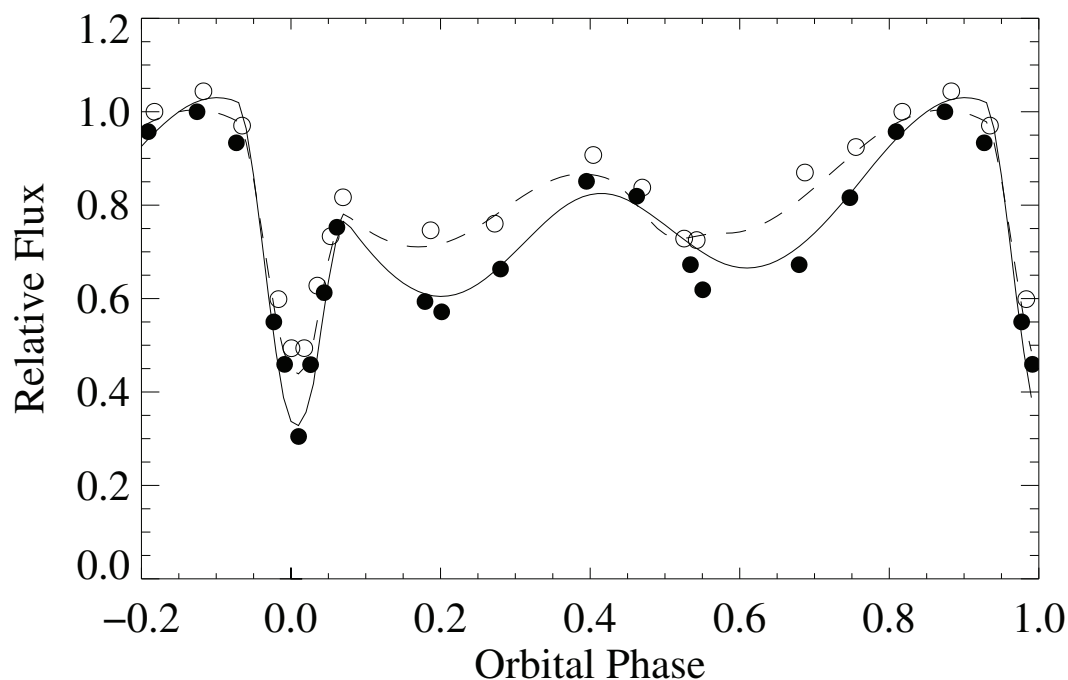


Fig. 7. This is the IUE light curve for R Ara. The solid circles are data points at 1320 Å and the open circles are at 2915 Å. The solid line is the W.D. model at 1320 Å and the dashed line is the model at 2915 Å. (Reed et al., 2010)

Notice the other two "dips" in the UV light curve of R Ara, one around phase 0.2 and the other near phase 0.6. Both of these dips behave like the primary eclipses, that is, they are both deeper at the shorter wavelength and therefore must be due to something cooler than the primary star eclipsing the primary star. Since we know that R Ara's orbital period is steadily increasing due to mass transfer (see Section 4), it is reasonable to assume that there is a cool accretion structure surrounding the primary star, which results from the mass transfer.

Cool "spots" were used in the W.D. code to model the dips in R Ara's UV light curve by treating them as spherical clouds in the line of sight to the primary star. In the model, the stars' surface temperatures are 12,500 K for the primary and 7,000 K for the secondary. The clouds have a temperature of 4,000 K. The inclination of R Ara's orbit, relative to Earth, is 78°. The solid and dashed lines in Figure 7 are the synthetic light curves produced by the W.D. code with the

cool clouds in the model. The solid line is the model at 1320 Å and the dashed line is at 2915 Å.

The locations of the cool clouds (spots) in the model reveal the general geometry of the accretion structure. An illustration of the model for R Ara is shown in Figure 8. The model shows an eccentric accretion cloud surrounding the primary star.

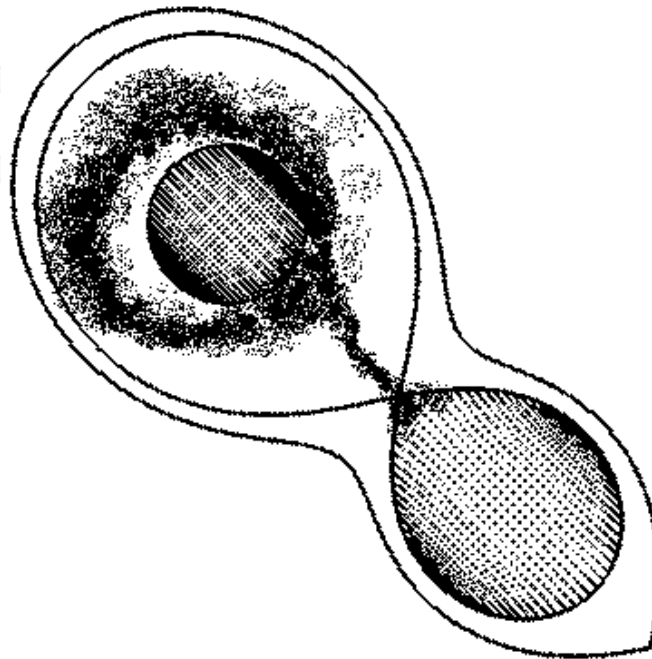


Fig. 8. This is an illustration of the model for R Ara showing an eccentric accretion structure surrounding the primary star.

The eccentric accretion structure, combined with R Ara's orbital inclination, produces the dips seen in the light curve. Three-dimensional views of the model for R Ara are drawn in Figure 9, showing the locations of the cool spots that best fit the data. When the accretion structure is farthest from the star, around phase 0.4, it is below our line of sight and we are looking over the accretion cloud directly at the primary star. At other times during the orbit, when the accretion structure is closer to the star, the cloud blocks our line of sight to the primary star and we see dips in the light curve.

The fact that the outside of eclipse dips in the light curve are quite variable indicates that the accretion structure is unstable and variable. When the accretion onto the star is more rapid, the accretion structure decreases in size and thickness and the system becomes brighter overall. When the accretion structure builds up again, the dips become deeper.

The question to ask is then, "can the accretion structure be eccentric and variable?" The answer is yes. Hydrodynamic simulations of mass flow in Algol-type binaries show that as an accretion disk builds up around the primary in a long-period system, it is eccentric. It's only after some time passes that the accretion structure becomes stable and starts to resemble a symmetric, circular disk (Richards & Ratliff, 1998). Because intermediate-period Algols, such as R Ara, oscillate between states of direct impact and indirect accretion, they likely undergo the rebuilding of their accretion structures fairly often and can therefore be regularly found with eccentric and variable accretion structures.

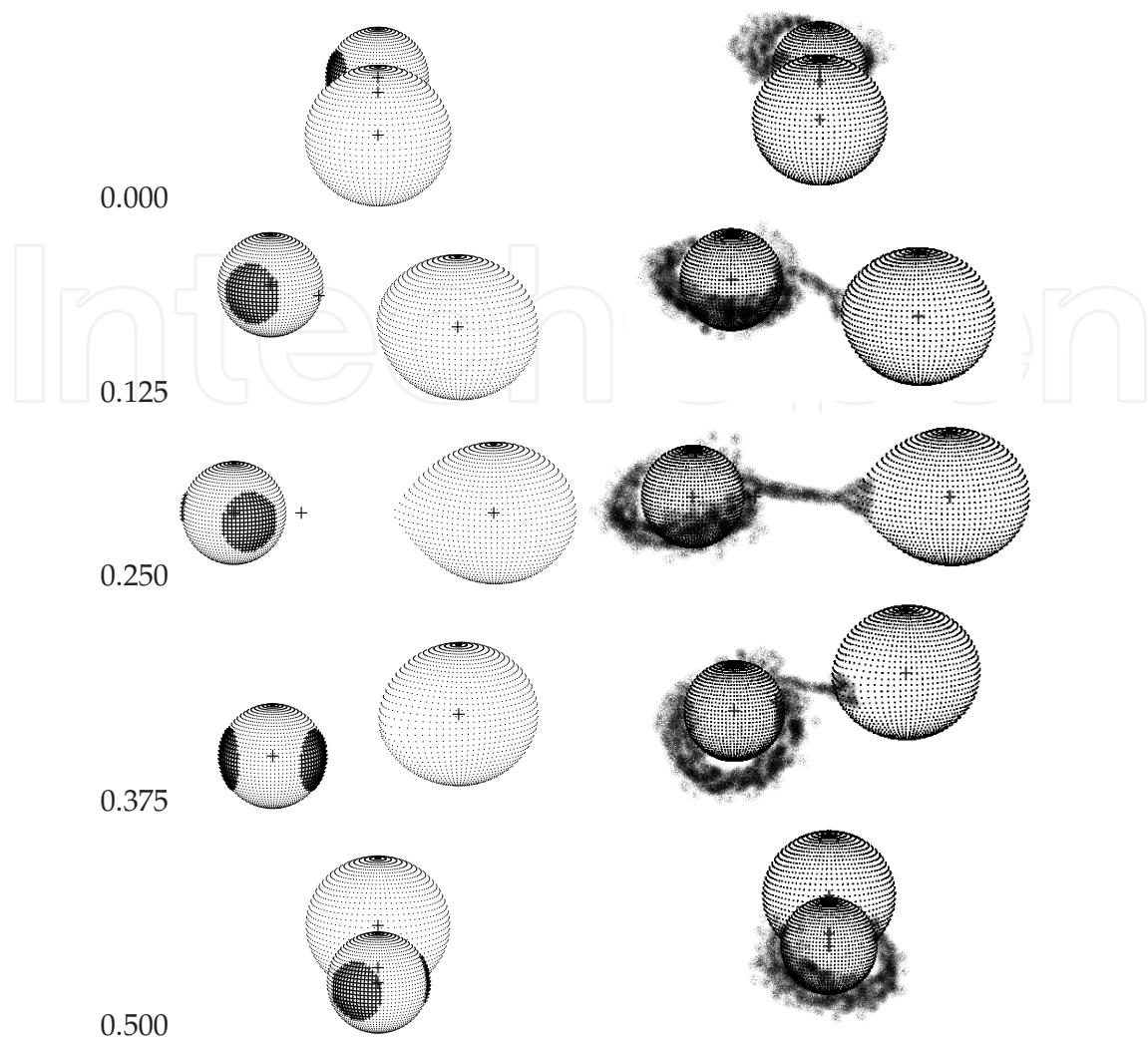


Fig. 9. These are 3-D views of the model for R Ara through the first half of its orbit. The left-hand column shows the W.D. model with the "cool clouds" (spots), and the right-hand column illustrates the corresponding proposed accretion structure. The orbital phase values for each view are listed to the left.

7. Future work

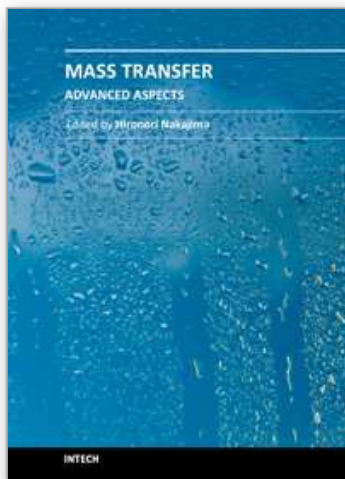
There are many neglected intermediate-period interacting binary star systems that deserve studying. Two examples are Y Piscium (orbital period = 3.7 days) and RV Ophiuchus (orbital period = 3.9 days), both of which show outside-of-eclipse variations in their latest light curves, which are more than 25 years old (Walter, 1973). Can the light curves of these star systems be modelled with eccentric accretion structures and orbital inclinations that lead to apparent eclipses of the primary star by the accretion cloud? If not, what else could explain the light curve variations? If something else can explain them, can it also explain the variations seen in R Ara?

On the theoretical side of the research, it is desirable to modify the W.D. code to account for eccentric accretion structures (disks or annuli). A limitation to the "cool cloud" method used in Section 6 is that the model does not account for the emission of light by the parts of the accretion structure not in the line of sight to the primary star. This condition is quite acceptable

for observations in UV light because, in that range of frequencies, the cool accretion structure emits very little light compared with the hot primary star. In visible, red, and infrared light, however, the accretion structure will emit more light than it does in the UV and the primary star will emit less light than it does in the UV, which makes the limitation of the "cool cloud" method more serious. Including the entire eccentric accretion structure in the light curve model will eliminate these limitations at all wavelengths and will provide a more accurate picture of the transfer of mass between these stars.

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Our knowledge of mass transfer processes has been extended and applied to various fields of science and engineering including industrial and manufacturing processes in recent years. Since mass transfer is a primordial phenomenon, it plays a key role in the scientific researches and fields of mechanical, energy, environmental, materials, bio, and chemical engineering. In this book, energetic authors provide present advances in scientific findings and technologies, and develop new theoretical models concerning mass transfer. This book brings valuable references for researchers and engineers working in the variety of mass transfer sciences and related fields. Since the constitutive topics cover the advances in broad research areas, the topics will be mutually stimulus and informative to the researchers and engineers in different areas.

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